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Control strategy of the module concrete thermal energy storage for parabolic trough power plants

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Abstract

Solid sensible heat storage is an attractive option for high-temperature storage applications in terms of investment and maintenance costs. Typical solid thermal energy storage systems use a heat transfer fluid to transfer heat as the fluid flows through a tubular heat exchanger embedded in the solid storage material. A one-dimensional unsteady model is developed using the modified lumped capacitance method for a solid cylindrical heat storage unit. A modular charging/discharging control strategy is proposed to improve utilization of the solid storage material. The control strategy of modular charging/discharging using two modules could increase the storage material utilization from 33.4% to 38%.

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Keywords: Solar thermal power; Concrete; Control strategy; Solid media sensible heat storage

1. Introduction

Thermal energy storage (TES) is essential for concentrating solar power (CSP) plant applications. The main advantages of integrating a TES in a CSP system include extended utilization of the power block, improved

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dispatchability, and extended life expectancy of components due to the reduction of thermal transients. Therefore, TES systems give CSP plants an edge over photovoltaic or wind power[1].

The TES using concrete as the heat storage media is a regenerative heat storage system where the concrete modules are cyclically heated and cooled by heat transfer fluid (HTF) flows. A tubular heat exchanger with a defined tube pitch is typically imbedded in the concrete module to allow HTF to flow [2].

Laing et al. [3] proposed the modular storage operation concept, which could increase by 100% the storage capacity. In this paper, we study the control strategy of the modular concrete TES using modified lumped capacitance method.

Nomenclature

a	inner radius of the cylindrical heat storage unit [m]
b	outer radius of the cylindrical heat storage unit [m]
C	specific heat [J/kg K]
di	inner diameter of the heat storage unit [m]
do	outer diameter of the heat storage unit [m]
h	heat transfer coefficient [W/(m^2 K)]
h_E	corrected heat transfer coefficient [W/(m^2 K)]
k_s	thermal conductivity of solid material [W/m K]
L	heat storage unit length [m]
P	heat transfer surface perimeter of the cylindrical surface [m]
$Q_{s,max}$	the maximum storage energy in the concrete storage module
$Q_{delivery}$	the discharged energy from storage module during the discharging
S_f	wetted area in the tube [m^2]
S_s	section area of solid material [m^2]
T	temperature [^{o}C]
t	time [sec]
U	average fluid velocity in the heat transfer tube [m/s]
ρ	density [kg/m^3]
φ	material utilization

Subscripts

ch	during the charging process
dis	during the discharging process
f	fluid
s	solid material
0	before charging or discharging
end	after charging or discharging

2. Model

Figure 1 shows a typical solid medium sensible heat storage module, with a tubular heat exchanger with collectors and distributors for the HTF embedded in the solid storage material. When charging, the hot heat transfer fluid heats the storage media as it flows through the tube heat exchanger. When discharging, the cold heat transfer fluid flows through the channels in the reverse direction and is heated by the hot solid storage media. During charging, the fluid temperature at the outlet of the storage module rises while during discharging, the fluid outlet temperature decreases with time.

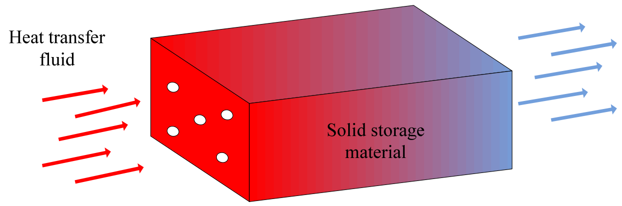


Fig. 1. Solid medium sensible heat storage module

A cross section of the solid storage module is shown in Fig. 2. The tubes imbedded in the storage module were arranged in a triangular pitch to obtain a better temperature distribution in the solid storage module. The entire storage module is made of many storage units with regular hexagonal cross sections. The analysis of the storage unit was then simplified by replacing the regular hexagonal shape by cylindrical storage unit geometry with the same cross-sectional area. The geometries are related as $d_o^2 = 2\sqrt{3}D^2 / \pi$.

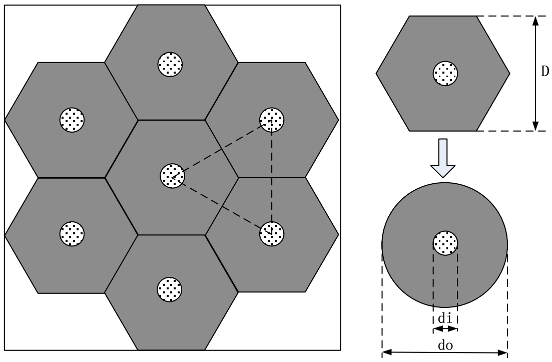


Fig. 2. Cross section of the solid storage module

The heat transfer fluid flow is uniformly distributed in the tube register, which means that the storage module will have the same thermal behaviour with the cylindrical heat storage unit shown in Fig. 3 during both charging and discharging processes.

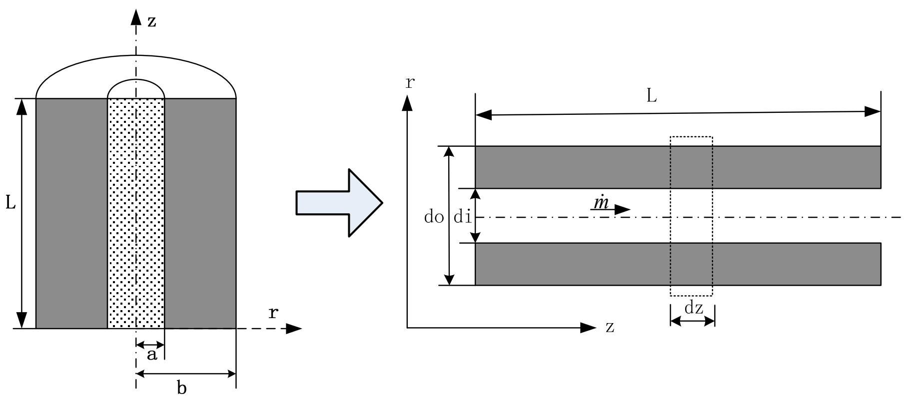


Fig. 3. Cylindrical heat storage unit model

The lumped capacitance method is applicable to the thermal conduction in the solid media in the radial direction; thus, $\partial T_s / \partial r = 0$. The 2D transient model for the solid storage unit can then be simplified to a 1D model. Assuming that the fluid flow rate $\dot{m}$ in the tubes is constant and the convection heat transfer occurs at the inner tube surface, the thermal energy balance for the fluid and solid material in the differential control volume dz in Fig. 3 are:

$$\frac{\partial T_f}{\partial t} + U\frac{\partial T_f}{\partial z} = \frac{h_E P}{\rho_f S_f C_f}(T_s - T_f) \tag{1}$$

$$\frac{\partial T_s}{\partial t} = -\frac{h_E P}{\rho_s S_s C_s}(T_s - T_f) \tag{2}$$

where h_E is effective heat transfer coefficient. The relation between heat transfer coefficient h and h_E is[4]:

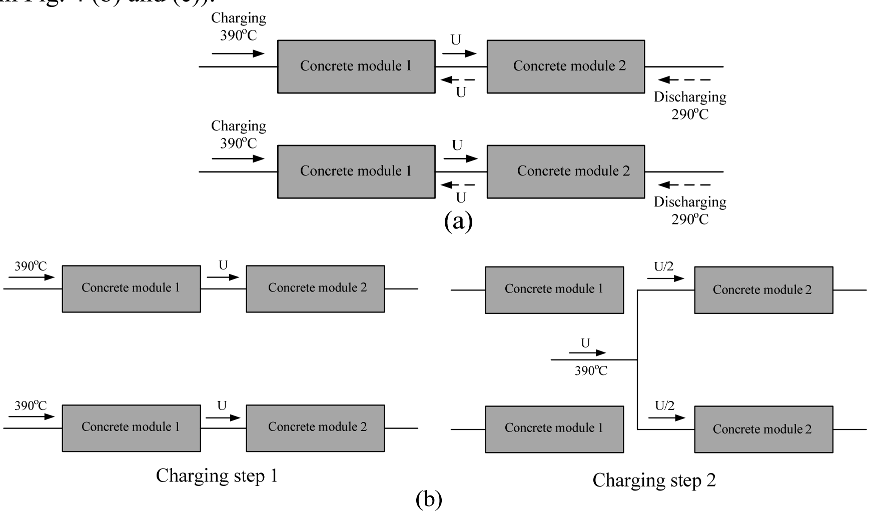
$$\frac{1}{h_E} = \frac{1}{h} + \frac{1}{k_s} \cdot \frac{4ab^4 \ln\frac{b}{a} - 3ab^4 + 4a^3b^2 - a^5}{4(b^2 - a^2)^2} \tag{3}$$

The validity of the effective heat transfer coefficient in Eq. (3) is checked by comparing with the analytical results[4].

3. Control strategy for storage module

When using a regenerative storage system like concrete storage system, an important operation parameter is the maximum fluid outlet temperature of storage system during charging process. As this temperature influences the inlet temperature for the collector field, it must be limited to avoid excess temperatures of the HTF in the collector. Another limitation is the minimum outlet temperature of the storage during discharging, as this defines the temperature in the turbine. Therefore, the storage is fully charged when outlet temperature of fluid exceeds the maximum inlet temperature for the collector. And the storage is fully discharged when outlet temperature of fluid is less than the minimum inlet temperature acceptable for the turbine.

Fig. 4 (a) shows a normal charging and discharging mode for two independent concrete TES systems. Because of the temperature difference in the axial direction of the concrete, the average temperature of concrete module near the outlet is still much lower than fluid when the concrete is fully charged and is still much higher than fluid when the concrete is fully discharged. Thus, the concrete cannot be fully utilized in the normal charging and discharging mode. Therefore, we propose a modular charging and discharging method. After normal charging or discharging process, we connected these two independent concrete TES systems together to extend the charging and discharging time (shown in Fig. 4 (b) and (c)).



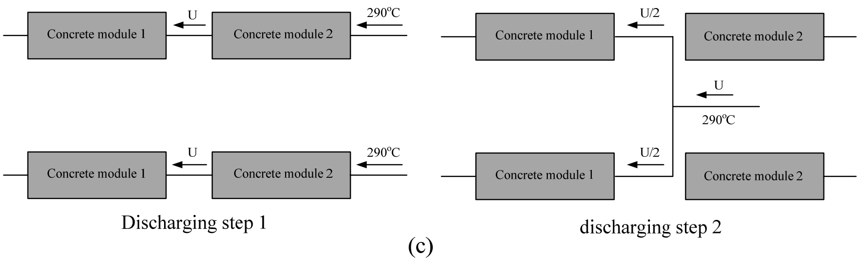


Fig. 4. Control strategy for storage module: (a) normal charging and discharging; (b) modular charging; (c) modular discharging

Firstly, we cut off the concrete modules near the inlet. Secondly, we connect the concrete modules near the outlet in parallel. We also cut off the fluid of one concrete TES system, which means the velocity in the concrete module will be half of that in normal charging and discharging mode. Since the temperature of the concrete module near the outlet is still much lower than fluid in charging process and much higher than fluid in discharging process, the fluid outlet temperature could still meet the system requirement for a while. Therefore, by using the modular charging and discharging mode, the average temperature of the concrete module could be higher at the end of charging and lower at the end of discharging, which means the concrete storage will be more efficient.

4. Results and discussion

High temperature concrete was used as the storage material and therminol VP-1 was used as the heat transfer fluid. The thermal properties of these materials are listed in Table 1.The maximum inlet temperature for the collector is set to 330°C, and the minimum inlet temperature acceptable for the turbine is set to 350°C. This means that the fluid outlet temperature cannot be higher than 330 °C during the charging process and lower than 350°C during the discharging process. The fluid inlet temperature is 390 °C in charging process and 290 °C in discharging process. The initial temperature of concrete is 290 °C before the first charging process. The charging and discharging time is set to 6 hours. Basing on the model mentioned in section 2 and according to the acceptable fluid outlet temperature and charging/discharging time, we could calculate the average velocity of the fluid in the heat transfer tube. The geometric parameters for storage module are: storage length L is 50 m, inner diameter of heat transfer tube di is 16 mm and diameter ratio η (=di/do) for the storage unit (Fig. 3) is 8.

Table 1 Material thermal properties

Material	Density (kg/m^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Viscosity (Pa.s)
Concrete (400°C) [1]	2250	1050	1.20	—
Therminol VP-1 (360°C) [5]	749	2480	0.0844	0.00017

Figure 5 shows the process of two tandem concrete modules in Fig. 4(a) from initial status to steady state after four charging and discharging cycles in the normal charging and discharging mode. The duration of a cycle (charging or discharging) is fixed to 6 hours. As a consequence, the velocity is calculated so that the fluid outlet temperature reaches 330°C after 6 hours of charging, which is the highest temperature accepted by the collector field. For the discharging, the velocity is calculated so that the fluid outlet temperature reaches 350°C after 6 hours, which is the lowest accepted temperature by the power block.

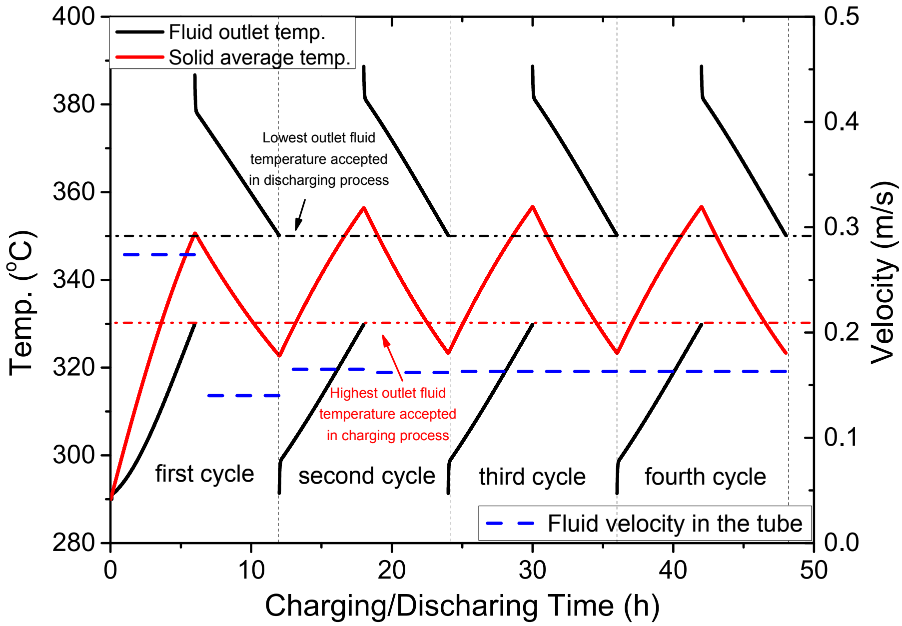


Fig. 5 The first four charging and discharging cycles in the normal charging and discharging mode

Actually, after 3 charging and discharging cycles, the storage modules are at steady state, and they work between 323.3 ^{o}C to 356.7 ^{o}C. At the beginning, the fluid velocities in the tube for charging and discharging are very different. But when the storage module is at steady state, the fluid velocity in the charging process equals to that in the discharging process, which is 0.163 m/s.

Figure 6 shows the solid temperature in axial direction of the storage module after charging and discharging.

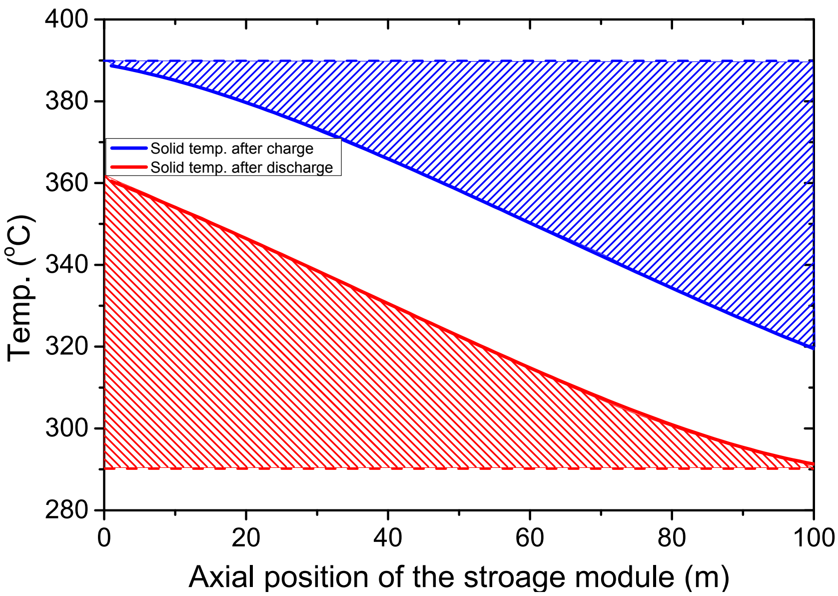


Fig. 6 Temperature distribution in axial direction of the storage module at the end of charging and discharging

After fully charged in normal charging/discharging mode, the outlet solid temperature of the storage module is 320 ^{o}C, which is much lower than the inlet fluid temperature. Similarly, the solid temperature at outlet of module is 360 ^{o}C after fully discharged, which is also much higher than the inlet fluid temperature. The temperature difference in the axial direction of the storage module reaches up to 70 ^{o}C. The blue area in Fig. 6 presents the temperature area which has not been used during charging process. The red area presents the temperature area which has not been used during discharging process. The white area between these two lines presents the temperature area which has been used by the storage system. This means that the storage material is not fully utilized in normal charging/discharging mode. Thus, we propose a new control strategy, based on modular charging and discharging, to decrease the temperature difference in the storage module axial direction and increase the utilization of the storage material.

Figure 7 shows the fluid and solid temperature during the modular charging and discharging.

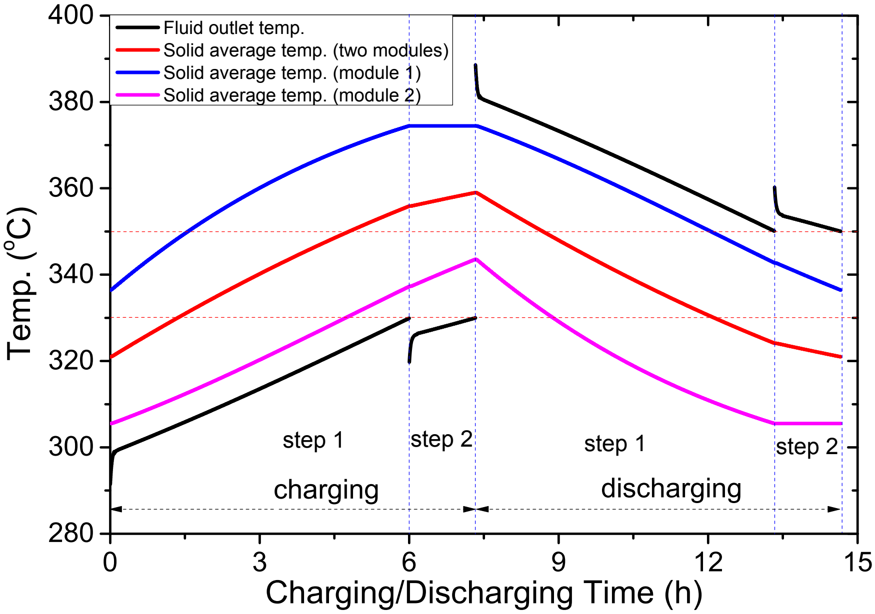


Fig. 7 Fluid and solid temperature in the modular charging and discharging mode (two modules)

The first step of the modular charging/discharging is the same as normal charging/discharging mode. At the second step of the modular charging, the module 1 is cut off and the module 2 of two independent concrete TES system are connected in parallel (Fig. 4b). The fluid velocity in the tube becomes half of the step one. Thus, the temperature of the concrete module 1 is constant, and temperature of the module 2 keeps increasing. Therefore, the solid average temperature of these two modules increases from 355.9 ^{o}C to 359.0 ^{o}C. Similarly, at the step two of the modular discharging, the module 2 is cut off and module 1 is connected in parallel (Fig. 4c). The temperature of the module 2 is constant, and temperature of the module 1 keeps decreasing. Thus, the solid average temperature of these two modules decreases from 324.1 ^{o}C to 321.0 ^{o}C.

Figure 8 shows the solid temperature in axial direction of the storage module after charging and discharging in the modular charging and discharging mode. The white area between two lines in Fig. 8 is larger than that in Fig. 6 because of the modular charging and discharging control strategy. This means that the modular charging and discharging control strategy proposed in Section 3 could improve the utilization of solid storage material.

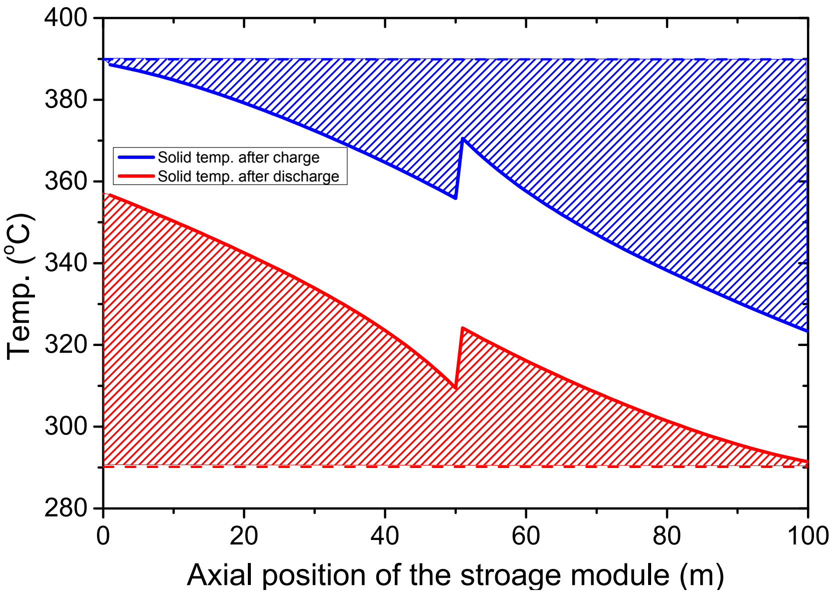


Fig. 8 Temperature distribution in axial direction of the storage module at the end of charging and discharging (modular charging and discharging)

Table 2 shows the utilization of solid storage material for normal and modular charging and discharging mode.

Table 2 The utilization of solid storage material for normal and modular charging and discharging mode

mode	Solid temp. before discharging	Solid temp. after discharging	Solid temp. difference	material utilization φ
Normal	356.67	323.32	33.35	33.4%
2 modulars	359.01	320.98	38.03	38.0%

The utilization of the solid storage material in Table 2 is defined based on the average temperature of the solid storage material,

$$\varphi = \frac{Q_{delivery}}{Q_{s,\max}} = \frac{m_s C_s (T_{s,0} - T_{s,\mathrm{end}})}{m_s C_s (T_{f,ch} - T_{f,dis})} \tag{4}$$

where $T_{s,0}$ is the solid temperature before discharging, $T_{s,\mathrm{end}}$ is the solid temperature after discharging, $T_{f,ch}$ is fluid inlet temperature during the charging process, $T_{f,dis}$ is fluid inlet temperature during the discharging process, m_s is the solid material mass of the storage unit($m_s = \rho_s S_s L$).

The work temperature difference of concrete module using modular charging/discharging mode is 5 °C greater than normal charging/discharging mode. Thanks to the modular control strategy, the utilization of solid storage material could increases from 33.4% to 38.0%. Therefore, comparing the normal charging/discharging method, the utilization of solid storage material is improved by 14% by using modular charging/discharging method.

5. Conclusion

A modular charging/discharging control strategy is proposed to increase the storage material temperature after charging process and decrease the storage material temperature after discharging process, which could improve the utilization of the storage material.

No matter the normal or modular charging/discharging mode, the concrete storage module could work at steady state after 3 charging and discharging cycles from initial state. Using normal charging/discharging mode, the temperature difference of the concrete is 33.35 ^{o}C whereas using modular charging/discharging mode, the temperature difference of the concrete increases to 38.03 ^{o}C using two modules. Therefore, the control strategy of modular charging/discharging could increase more than 14% of material utilization. These results are promising and demonstrate the feasibility of the modular control strategy mode. Next, we will do it with 4 and more modules to enhance the performances of the system.

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